PRODUCTION QUALITY IMPROVEMENT BASED ON 1D DIGITAL TWIN

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One of key component of hydrostatic close circuit pump or motor is hydrostatic control. The control influences their performance and behavior. That is the reason to pay high attention on the qualitative aspects. One of them is the First Pass Yield (FPY) indicator.The aim of the paper is to show simulation deployment into the problem solving of leakage issue. High leakages caused low FPY indicator at production line tests. A digital twin was fundamental source of useful information. Selection and finding out the most influencing parameters were based on sensitivity analysis and correlation with the test data and production processes. Final parameters have been found out from their combinations itself in relation to the machining. Outcome of the analysis leads to quality improvement of machining. This improvement of production process of hydrostatic controls resulted to increase FPY indicator close to 100% and reduce its variation into almost 0%.

KEYWORDS

hydrostatic control, sensitivity analysis, simulation, digital twin, leakage

1 INTRODUCTION

An effort of simulation engineers is to speed up development, cut costs, and reduce physic testing. On the other hand, simulations can help to reveal causes of the unexpected or unwanted behavior either components or complex systems [MathWorks1 2018]. Modeling and simulations might be valuable tools for cost reduction by optimization of existing design parameters in relation to production process what is described in this paper.

The more of new approaches are applied and fidelity of the model are achieved the more complex the model becomes or response of the model might be risky. Therefore, the risk should be mitigated by introducing Model-Based Design (MBD) gradually. It means to build model from simple to complex with respect to time and fidelity demand. Practically, this means that any new design or tools and process changes need to be introduced incrementally [MathWorks2 2018]. From our point of view, the digital twin means to create 1D parametric model of the product, where parameters come from design. To build the model as digital twin of product is quite time demanding and challenging task with many sub-models, features, physical equations and other details linked and they must be verified. For close study this field see detailed equations which were implemented from Ivantysinova's and Manring's books [Ivantysinova 2001,Manring 2005] in our case. Typically, once a subsystem of the model has been shown to work well, it might be incorporated within the rest of the model or system as shows [Aberg 2018]. If a simulation model matched all key trends of measured data in test laboratory with acceptable fidelity, then a model is assumed as validated digital twin. Validation process is very complex because there are many inputs which could influence test results and matching with simulation results. Verified models of components could help to solve specific design problems as they occurred in products. This approach was applied in servo controls for hydraulic pumps and motors like it is shown in Fig. 1 and Fig. 2. If a virtual model of product as product twin is built, targeted benefits could be gain even without making full scale models of the product in real environment. Various extreme operating conditions could be tested and set the limit boundary conditions for reliable working of product during its lifetime. The better understanding how the product is working is fundamental benefit. The immediate advantage of MBD is using of simulations to test and validate designs for prototyping and testing. Later, there can be considered and adopted advanced tools and practices.

Figure 1. Pump with servo control

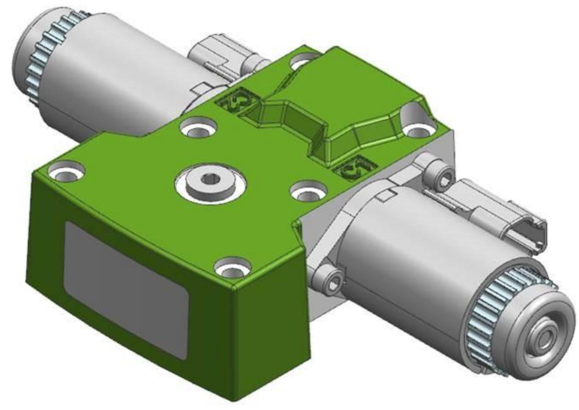

Figure 2. Servo control from CAD

Product development and innovation processes are changing. Effort to speed up development, reduce costs, decrease time to market, increase efficiency and improve quality, the boundaries what are possible to change are constantly being pushed. To stay competitive the development process must promote and nurture creativity and innovation.

2 DESCRIPTION OF THE PROBLEM

The parametric model as the digital twin is a basis for agile root cause analysis if some comes from manufacturing. In the Fig. 3, you can see workflow diagram of inquiry. The problem statement could arise in anyone stage of analysis process. An issue came from quality check and it initialized further investigation. We measure every servo control at the final check. Therefore, we had available plenty of data sets (correct and faulty units as well), but to simplify big data processing and speed up handling with that, we selected just representative measurements for correct characteristics near to the ideal. All correct servo controls had almost identic characteristics, just faulty products had significantly different characteristics. Low FPY at production test stands was indicator that quality requirements are not satisfied. That was the impulse to start root cause analysis. A reason why the final product did not pass final quality control was quite high leakages against our internal requirement. Measurements were done after several work cycles to stabilize fluid flow and remove air bubbles from cavities. Leakage means a difference between supply flow and flow to servo. That means internal losing fluid flow to the oil tank. Challenge of the inquiry was how to reduce redundant leakage. There were available 2 ways how to treat high leakage. Design might be changed, or tolerances might be constrained strictly, if it is relevant.

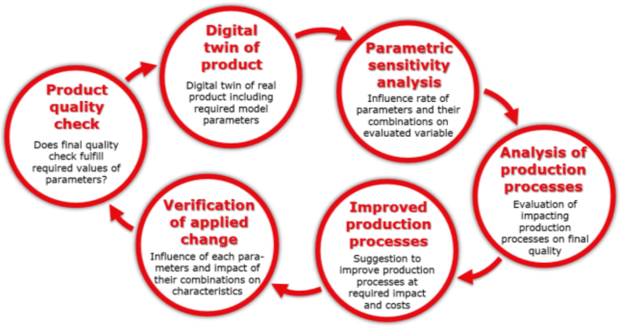

Figure 3. Diagram of steps in analysis

For the purpose to reduce redundant leakage, it is most important to find out the best parameters with positive impact on leakage decreasing. Input parameters for an optimization came from production drawings. Several closely connected among each other were merged in other to reduce number of parameters, which were a few tenths. The most studied output characteristics were pressure vs electric current, leakage vs electric current dependence and swash angle vs electric current dependences, but the leakage was the key for the analysis.

3 SOLUTION

Input parameters of digital twin were defined based on dimensions, tolerances and other parameters in drawings with regard of function and behavior. Some coupled dimensions were mixed together into the one parameter to decrease number of input parameters. Basis schema how the servo control works is expressed by block diagram in Fig. 4. 1D parametric model was based on that and created in MATLAB/Simulink. The servo control is symmetric with A and B side.

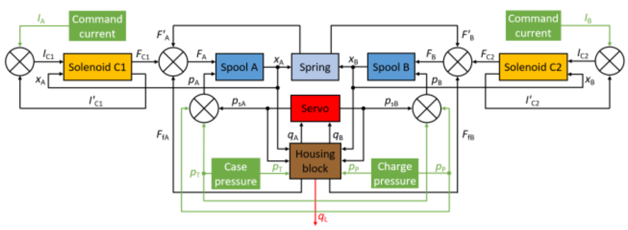

Figure 4. Block scheme of servo control

Where	I	– electric current,
	F	–force,
	F_f	–flow force,
	p	–pressure,
	p_s	–servo pressure,
	q	–fluid flow,
	q_L	–leakage,
	x	–stroke,
superscript ʻ		– feedback variable.

Meaning of other variables is evident from the Fig. 4. Every block in the block diagram represents one hardware component giving feedback to other parts. Command current in range 0 – 1520 mA, case pressure 1 bar, charge pressures 25 bar and design parameters were the inputs. Our attention was focused on leakage output from the servo control. The expressions for the evaluated output (q_L) would be enormous and there would be little profit in writing them out from object of this paper point of view. Hardware components with design parameters, which are included in main mask, were represented by system of equations deeper in sub-models. The model contains apart of all equations one valuable feature, which is calculation of flow forces at very small openings of pilot edges according to Wu et al. [Wu 2003]. They used and verified empirical equation for flow area

$$A(x) = \frac{wx}{1 - e^{\frac{x}{d_0}}} \qquad (1)$$

where	$A(x)$	–flow area,
	w	–rectangular orifice width,
	x	–orifice opening,
	d_0	–height of square type orifice at thenull position.

The height of the orifice, d_0, can be expressed as

$$d_0 = \sqrt{(2r + c)^2 + 4r^2} - 2r \qquad (2)$$

where	r	– radius of corner break (chamfer)on the pilot edges,
	c	– clearance between spool andhousing.

Sensitivity analysis pointed out the parameters of the model, which have significant impact on behavior of a servo control. Trend lines coming from sensitivity analysis shown how the key parameters shape characteristic lines. Here was applied a reverse procedure as it is usual for sensitivity analysis to match up simulation outcomes with test data. Into the analysis was selected 3 representative measurements from the test data set. Input test data were regularized to create one group of reference characteristic lines. However, we could not have neglected combinations of parameters, because synergy of some parameters significantly changes characteristics of the servo control. In exploration, we used the reference lines for comparison against simulations in Fig. 5. You might assume real edge looks like sharp edge and ideal shape of edge might be like smooth edge as they are sowed in Fig. 6.

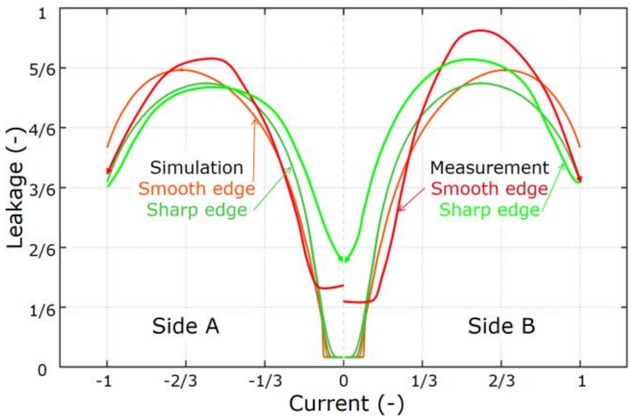

Figure 5. Comparison of leakages from simulation against measurement

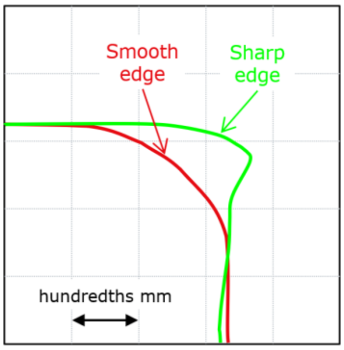

Figure 6. Shape of corner breaks on the pilot edges

Simulations and measurement were done for oil Shell Tellus S2 M 46 at charge pressure 25 bar, case pressure 1 bar, temperature 50 ˚C and both solenoids were energized and deenergized in cycle.

An effort is to match up output characteristics from simulations with test results thanks to various combination of input parameters. An aim was to achieve a combination of key parameters to the best fitting of simulation trends with measurements. Specially, leakage-current curves should fit measurement data. Outcomes from the sensitivity analysis helped us to understand impact of each parameters on the characteristics. Number of incorporated parameters into final simulation case matching test data were eliminated as much as possible, but kept connection between them. Hence, we restricted combination of parameters as few as possible. Finally, here were 2 criteria – sensitivity analysis and correlation with measurements which we considered.

In next step, we explored what manufacturing processes determine values of key impact parameters. Additional challenge was to analyze and evaluate how much machining and tooling influence on the key parameters. Looking on manufacturing processes in detail opened space for improving final values of parameter and their tolerances by change of machining, tooling and other processing sub-step.

4 RESULTS

Result of complex analysis including simulations, measurements and processing technologies were knowledge that key parameter for quality requirements and issue of high leakages was close connected with pilot edges as it shows Fig. 7.

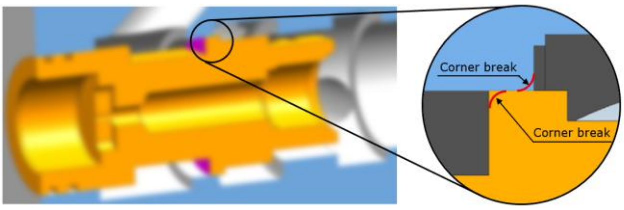

Figure 7. Shape of corner breaks on the pilot edges

These edges are functional in meaning of right working of a servo control. When we selected one parameter, we were possible to focus on this parameter and explore it deeper. In detailed view, we could evaluate overlaps or underlaps, shape of corner breaks, some notches coming from machining as well and others. A design used to assume nice rounded shape of corner breaks on the pilot edges, but microscopic measurement might show different shape of edges. Real shape of edges or corner breaks depends on machining technologies and it differed from ideal, nice rounded edge considerably as the Fig. 6 shows. That was place where all observed troubles were arising from.

Here are also several processes as milling, several-step deburring, brushing involved into the result value. We must take care of their exact fulfillment. At the end we could select just one process to raised up quality indicators rapidly. After the verification of the remedy it showed to be only one necessary thing to improve. Impact just one, but crucial remedy was quite huge on final quality increasing.

5 CONCLUSIONS

The simulation was based on upgrade of existing model and sub-systems in library. Testing and measurements are realized on existing test stands and hardware. Therefore, these simulation and testing background was not included in estimation of saved effort. The root cause analysis from pre-processing to post-processing was 6 weeks. The root-cause analysis based on simulations included the analysis of 18 parameters (with minimal, nominal and maximal values) and their combinations. Approximately 60 combinations of limit values of several parameters were analyzed and 4 combinations were selected as high influencing leakages at the end. Final solution is deduced from this result. One loop in prototyping and physical testing by trial and error to analyze one design variation might take comparable time as whole root-cause analysis done by simulation. Based on that we might estimate approximately 80 times shorten lead time to deliver the results. Cost saving might be assumed as sum of costs for prototyping and testing on production line and loss due to interrupted manufacturing because of testing on production test stand. Total cost saving by simulations are even higher because costs for manufacturing of hardware is not expressed, but it is substantial costs.

The intention is pointed out the facts that thanks to remedy, scraps were significant reduced and required quality indicator reach to almost at 100% FPY. Production was stable and without high variations of leakages after the remedy. The highest cost savings were in production line thanks to early remedy with huge impact on manufacturing. Analysis pointed out how important is to observe drawing requirements, take care about technologies processes and their relevance for ensuring required and guaranteed quality indicators as well. It all would not be achieved without deploying modeling and simulations in MBD. Afterwards, the work showed how enormous impact just one, but crucial operation can have on final quality.

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